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OF

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FOR

**METHOD AND APPARATUS FOR ACCURATE ALIGNMENT OF IMAGES IN DIGITAL IMAGING
SYSTEMS BY MATCHING POINTS IN THE IMAGES CORRESPONDING TO SCENE ELEMENTS**

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FIELD OF THE INVENTION

The invention relates generally to the field of digital imaging, and more particularly to systems and methods for aligning images in digital imaging systems.

BACKGROUND OF THE INVENTION

Digital imaging systems record many images of a scene for various applications. Some applications require accurate knowledge of the positions of points in the scene, in relation to a three-dimensional coordinate system, which, in turn, requires accurate knowledge of the locations of projections of the points in the respective images. One illustrative application is photogrammetry, in which information such as distances between points in a scene, heights of points in the scene above a reference level, and so forth, can be determined from measurements between and among points on the two-dimensional images that were recorded of the scene. Another application is three-dimensional virtual reconstruction of objects in a scene from the two-dimensional images that were recorded of the scene. Such virtual reconstructions can be used, for example, for precise measurement of features of the reconstructed objects.

In some applications, it is desired to measure certain features in a scene with a high degree of accuracy. Such measurements either require that information about the scene be provided to the imaging system, or that the imaging system be able to extract such information from the images in an automated manner. In either case, it is helpful to the imaging system if there are certain features in the scene, as recorded in the images, that can be accurately detected and whose positions and sizes can be accurately measured. These features, which may be referred to as "anchor points" or "targets," can be planted artificially within the scene to provide reference information for the imaging system. The targets possess predetermined optical characteristics and can readily be automatically differentiated by the imaging system from other objects in the scene. In addition, the imaging system knows the positions in the scene, relative to a three-dimensional coordinate system,

1 of respective ones of the targets. The imaging system, in turn, will need to be able to accurately
2 determine which pixels in the images recorded of the scene relate to respective ones of the targets
3 in the scene. Since the imaging system will need to make a quick and accurate identification of the
4 targets, several problems can arise. In particular, generally special consideration needs to be given
5 to the type of material of which the targets are made, their shapes, and so forth. One technique has
6 been to provide the targets with specific shapes and contours, which can be coded in a predetermined
7 way to ensure that they will stand out and be readily distinguishable from the other objects in the
8 scene. The targets can be made from materials with predetermined surface characteristics, such as
9 diffuse or highly reflective, as long as their shapes and/or reflectance differ considerably from the
10 expected shapes and/or reflectance of the objects in the scene that are to be subject to mensuration,
11 reconstruction, and so forth.

12 Another technique involves the use of directional reflecting materials, such as retro-reflective
13 materials for the targets. An object made of a retro-reflective material reflects light that is incident
14 thereon predominately back in the direction of the light source from which the light originates.
15 Types of retro-reflective materials are well known, and are used in, for example, signs, safety
16 reflectors and so forth. The reflection characteristic of the material is generally independent of the
17 angle of incidence of the light on the surface over a relatively wide range of incidence angles. If the
18 objects in the scene that are to be subject to mensuration, reconstruction, and so forth, are not made
19 of retro-reflective materials, the reflective characteristics of their surfaces will differ substantially
20 from the reflective characteristics of the targets, and, if they are properly illuminated, as will be
21 described below, it can be relatively easy for the imaging system to distinguish between the targets
22 and the other objects in the scene.

23 Yet another technique involves the use of targets that essentially provide holes in the scene
24 by, for example, absorbing light incident thereon or by reflecting the light in such a manner that it
25 will not be directed to the image recording device(s) when images thereof are being recorded.

26 In order to accurately determine the positions of the targets, they need to be uniformly
27 illuminated so that the appearance of each target will not vary over the field of view or from image

1 to image. However, if the imaging system requires structured illumination, which provides a
2 textured appearance for surfaces that what might otherwise appear relatively featureless, the
3 simultaneous use of structured illumination and uniform illumination will typically reduce the effect
4 of the structured illumination on the scene, which, in turn, can interfere with the imaging system's
5 ability to perform its mensuration, virtual reconstruction, and so forth, operations. On the other
6 hand, if structured lighting is used alone or predominately to illuminate the scene, including the
7 targets, the appearance of respective ones of the targets can change from image to image, which will
8 make it more difficult for the imaging system to identify the projections of a respective in the various
9 images. In addition, the structured illumination can cause projections of the targets to appear
10 deformed, which can increase the difficulty of accurately determining their locations in the images.
11 Finally, if both structured lighting and uniform illumination are used, but for recording of successive
12 images from what is hoped to be the same direction, problems can arise since one or both of the
13 camera or other device that records the images and the object(s), including the target(s), in the scene
14 can vibrate or otherwise move, which, in turn, can cause inaccuracies in registration between the two
15 images. The time interval between times at which the camera can record successive images can vary
16 based on a number of variables, including, for example, image size and resolution, image buffer
17 download time, and so forth, but often the time interval is long enough for such differences to have
18 adverse effects. This can significantly reduce the accuracy of the mensuration, reconstruction, and/or
19 other operations that the imaging system may be required to perform.

20 SUMMARY OF THE INVENTION

21 The invention provides new and improved systems and methods for accurately aligning
22 images in a digital imaging system.

23 In brief summary, the invention provides a new digital imaging system and method that
24 facilitates the location of anchors or targets in images of a scene. The invention provides two
25 general aspects. In one general aspect, the digital imaging system makes use of, for example,
26 differences as between the properties of the surfaces of the targets and the properties of the surfaces

1 of the objects that are to be mensurated, reconstructed, etc., to facilitate providing uniform
2 illumination of the targets when recording a set of images of the scene, thereby reducing noise that
3 may arise in connection with determining the locations of the targets if they were illuminated by
4 structured illumination, while contemporaneously providing that the objects can be illuminated by
5 structured illumination when the images are recorded. In this aspect, the digital imaging system can
6 use the positions of the targets in the images to relate a local coordinate system associated with the
7 image set to a global coordinate system.

8 A second general aspect makes use of one or more of a plurality of algorithms to determine
9 the locations of targets in the images of the scene in the respective objects. In this aspect, the digital
10 imaging system records two sets of images, including a baseline set and a working set. The baseline
11 set is recorded using uniform illumination, with the baseline set comprising only images of the
12 targets. The working set is recorded using structured illumination, with the working set comprising
13 image of both the targets and the objects. The working set is used in connection with mensuration,
14 virtual reconstruction, etc., and one or more of the algorithms are used to determine the likely
15 positions of the targets in the images in the working image set, and to determine transformations
16 between the baseline and working image set such that the local coordinate system associated with
17 the working image set can be related to the global coordinate system.

18 BRIEF DESCRIPTION OF THE DRAWINGS

19 This invention is pointed out with particularity in the appended claims. The above and
20 further advantages of this invention may be better understood by referring to the following
21 description taken in conjunction with the accompanying drawings, in which:

22 FIG. 1 schematically depicts a digital imaging system constructed in accordance with the
23 invention;

24 FIG. 2 schematically depicts a camera useful in one embodiment of the digital imaging
25 system depicted in FIG. 1; and

1 FIGS. 3 through 7 depict flowcharts describing operations performed by respective
2 embodiments of the digital imaging system in connection with the invention.

3 **DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT**

4 FIG. 1 schematically depicts a digital imaging system 10 constructed in accordance with the
5 invention. The digital imaging system 10 includes an optical head 11, a rig 12, and image processing
6 subsystem 13. The optical head 11 comprises one or more cameras 14A,..., 14N (generally identified
7 by reference numeral 14n) each of which can record images of a scene 15. The rig 12 is provided
8 with a motion capability, for example, that can translate and/or rotate the optical head 11 relative to
9 the scene 15 to allow the cameras 14n comprising the optical head 11 to record sets of images of the
10 scene 15 from a plurality of positions and angular orientations. In one embodiment, the cameras 14n
11 comprising the optical head 11 include image sensing and recording media such as CCD (charge
12 coupled devices) or CMOS (complementary metal-oxide semiconductor) devices, which record
13 images in electronic form, and the cameras 14n download the images to the image processing
14 subsystem 13 after they are recorded for processing.

15 The particular processing operations performed by the image processing subsystem 13 will
16 depend on the particular application for which the digital imaging system 10 is being used. If, for
17 example, the digital imaging system 10 is to be used for mensuration of elements of the scene 15,
18 the image processing subsystem 13 can determine distances between points on selected ones of a
19 plurality of object(s), generally identified by reference numeral 16, in the scene, distances between
20 points on objects 16 in the scene and some reference plane such as a floor, and the like. Similarly,
21 if the digital imaging system 10 is to be used to generate a virtual three-dimensional reconstruction
22 of one or more of the objects 16 in the scene, it can generate such a virtual reconstruction using one
23 or more of a number of techniques that are known to those skilled in the art. In addition to the
24 object(s) 16 that are to be measured, reconstructed, and so forth, the scene is also provided with a
25 plurality of anchor points or targets, generally identified by reference numeral 17, whose positions
26 relative to a selected global coordinate system are known. As is appreciated by those skilled in the

1 art, a virtual reconstruction of a portion of a scene, from a set of images of that portion of the scene,
2 will be in relation to a coordinate system that is related to that set of images, and the targets 17
3 facilitate relating such local virtual reconstructions to a unitary global coordinate system. Similarly,
4 if the features of the objects undergoing mensuration require that multiple sets of images be recorded
5 for the mensuration, the coordinates of the features as determined using the respective sets of images
6 will need to be related to a unitary global coordinate system to enable them to be mensurated, and
7 the targets facilitate that operation as well.

8 The scene 15 is illuminated by one or more light sources, generally identified by reference
9 numeral 20. As will be described below, at least some of the light sources provide a structured
10 illumination for the scene 15. Structured illumination is used to provide a pattern or texture on the
11 object(s) 16 in the scene 15 that aids the image processing subsystem 13 in identifying, in a set of
12 images that are used in generating a local virtual reconstruction, points in the images in the set that
13 are images of the same point in the scene 15, which is useful in determining their coordinates in the
14 respective local coordinate system. Generally, in a scene 15 that includes targets 17 in addition to
15 the objects 16 that are to be subject to mensuration, virtual reconstruction, and the like, at least two
16 successive images are recorded, one with texture illumination that is used in virtual reconstruction
17 of object 16 and another with uniform illumination to measure the targets 17. In this case any
18 relative movement between the object and the optical head that occurs during the image acquisition
19 of the two images, as commonly happens in industrial environment, degrades the accuracy of the
20 global measurement. Attempting to locate the targets 17 using only structured illumination will
21 result in poor determination of the location of the targets since their images are deformed by the
22 structured illumination's texture. The invention provides several arrangements, in two broad classes,
23 that allow the digital imaging system 10 to record of images of scene 15, including both the objects
24 16 and targets 17, that are illuminated by structured illumination while enabling the accurate
25 measurement the location of targets 17. This will allow the digital imaging system 10 to perform
26 its mensuration operations, generate virtual reconstructions and the like, and determine their
27 positions in the global coordinate system accurately with immunity to vibrations or other relative
28 movements between the object and the optical head.

1 As noted above, the invention provides two broad classes of arrangements. In one broad
2 class, the invention provides a set of arrangements that make use of selected lighting and image
3 recording conditions, which, in combination with surface characteristics of the targets 17 and objects
4 16, allow the targets 17 to be readily differentiated from the objects 16, and which further allow the
5 full target to be captured in the images without deformation that may be due to, for example, the
6 texture that is due to structured illumination provided for the objects 16. In a second broad class,
7 the invention provides a set of arrangements that make use of various algorithms to identify and
8 distinguish targets 17 from the objects 16 in the images and to accurately determine the positions
9 of the targets in the images despite the fact that images thereof are recorded while they are
10 illuminated by structured illumination. The algorithm-based techniques can be used with the
11 lighting condition/target surface characteristic techniques, but the algorithm-based techniques can
12 also be used instead of the lighting condition/surface characteristic techniques when no lighting
13 condition/target surface characteristic technique can be used. Digital imaging systems constructed
14 to make use of a lighting condition/target surface technique in accordance with the invention will
15 be described first, followed by digital imaging systems constructed to make use of an algorithmic
16 technique in accordance with the invention.

17 Generally, digital imaging system 10 includes two sets of light sources, generally identified
18 by reference numerals 20A and 20B. Light sources 20A are configured to provide unstructured,
19 uniform illumination. On the other hand, light sources 20B are configured to provide structured
20 illumination. In accordance with one aspect of the invention,, the surfaces of targets 17 are retro-
21 reflective and the surfaces of objects 17 are relatively diffuse. In that case the optical head is
22 configured to locate the sources 20A near the lenses of the cameras and preferably the sources 20A
23 are of a ring type in order to efficiently collect the retro reflection from the targets, and sources 20B
24 are located far from the lenses of the camera in order that only small fraction or any of the light
25 emitted by them and reflected by the retro reflective targets will enter the lenses of the cameras. In
26 that case, the intensity of the unstructured, uniform illumination provided by the light sources 20A
27 for targets 17 can be far lower than the intensity of the structured illumination provided by light
28 sources 20B for objects 16.

1 Since the surfaces of the targets 17 are retro-reflective, they can readily reflect the relatively
2 low-level illumination provided by light sources 20A. On the other hand, since the surfaces of
3 objects 16 are generally relatively diffuse, they will not reflect the illumination provided by light
4 sources 20A to any significant extent, in relation to the extent to which they will reflect the
5 structured illumination that is provided by the light sources 20B, thereby maintaining the texture
6 provided by the structured illumination. In that case, the two sets of light sources 20A and 20B can
7 illuminate the scene 15 contemporaneously, and the targets 17 will reflect the unstructured, uniform
8 illumination provided by light sources 20A, and so the targets 17 will appear to be uniformly
9 illuminated in the images recorded by the cameras 14n.

10 The image processing subsystem 13 can process the images both for mensuration
11 information, virtual reconstruction, and so forth of objects 16 since they were illuminated with
12 structured illumination. On the other hand, the image processing subsystem 13 can process the
13 image to determine accurately the location of targets 17 as they illuminated with uniform
14 illumination in order to provide alignment information by which the local coordinate system that is
15 associated with the positions of the cameras at which the images were recorded can be related to the
16 global coordinate system.

17 In accordance with another aspect of the invention the surfaces of target 17 in the scene 15
18 are spectrally sensitive to and thus will absorb and or reflect light having different wavelengths. In
19 that case digital imaging system 10 includes two sets of light sources, generally identified by
20 reference numerals 20A and 20B. Light sources 20A are configured to provide unstructured,
21 uniform illumination at a wavelength that will be reflected from the surfaces by targets 17. On the
22 other hand, light sources 20B are configured to provide structured illumination at a wavelength that
23 will not be reflected by surfaces of targets 17. The objects 16 should reflect the illumination provided
24 by light sources 20B and may also reflect the illumination provided by light sources 20A. Preferably,
25 the intensity of light sources 20A is less than the intensity of light sources 20B or the emitting
26 spectrum of light sources 20A is narrower than the spectrum emitted by light sources 20B as to
27 dominate the reflection of light from light sources 20B by objects 16, over the reflection of light
28 from light sources 20A by objects 16.

1 Since the targets 17 reflect only the uniform light emitted by light sources 20A and they do
2 not reflect the structured light emitted by light sources 20B their images as recorded by cameras 14n
3 will appear uniform and will not be deformed by the structured illumination. Despite the fact that
4 objects 16 reflect both the uniform and the structured illumination, their images as recorded by
5 cameras 14n will appear textured, since, as described above, the intensity of illumination provided
6 by light sources 20A is less than the intensity of the illumination provided by light sources 20B, or
7 alternatively the emitting spectrum of light sources 20A is narrower than the spectrum emitted by
8 light sources 20B as to dominate the reflection of light originated from light sources 20B by objects
9 16, over the reflection of light originated from light sources 20A by objects 16,

10 In accordance with another aspect of the invention the digital imaging system 10 includes
11 two sets of light sources, generally identified by reference numerals 20A and 20B. Light sources
12 20A are configured to provide unstructured, uniform illumination at one wavelength band and on
13 the other hand light sources 20B are configured to provide structured illumination at another
14 different wavelength band. The respective cameras 14n and image processing subsystem 13 can be
15 configured to distinguish between the portions comprising the targets 17 and the objects 16. For
16 example, if the uniform illumination provided by light sources 20A has a wavelength that is in the
17 red portion of the visible spectrum, and if the structured illumination provided by light sources 20B
18 has a wavelength that is in the blue portion of the visible spectrum, the image processing subsystem
19 13 can process separately, in each image as recorded by a respective camera 14n, portions that are
20 in the red portion of the visible spectrum as comprising images of the targets 17 in the respective
21 image, and portions that are in the blue portion. In this case the blue image will contain images of
22 both the object 16 and the targets 17 in structured appearance and will be used for mensuration,
23 reconstruction and so forth of object 16 and the red image will contain images of both object 16 and
24 targets 17 in uniform appearance. The image processing subsystem 13 can distinguish between the
25 targets and the object based on several conventional methodologies, including, for example, those
26 based on gray level, edges, shape, and others as will be apparent to those skilled in the art. The
27 location of the image of targets 17 can be accurately determined from the images recorded using
28 uniform illumination. In addition, although the above example makes reference to illumination in

1 wavelengths in the visible spectrum, it will be appreciated that the illumination may be in any part
2 of the electromagnetic spectrum.

3 As an alternative to having the cameras 14n record images in color, the respective cameras
4 can record images monochromatically in such a manner as to facilitate distinguishing between
5 different wavelength bands. An illustrative camera, identified by reference numeral 30, is
6 schematically depicted in FIG. 2. With reference to FIG. 2, the camera 30 includes a housing 31 that
7 houses an image recording medium 32. A lens system 33 directs light received from the scene 15
8 to a beam splitting arrangement 34. The beam splitting arrangement 34, in turn, splits the light,
9 represented by ray 35, that is received from the lens system 33 into two portions 35A and 35B. The
10 portion 35A of the light from the beam splitting arrangement 34 is filtered by a filter 36A that passes
11 light in the wavelength provided by light source 20A and blocks the light in the wavelength provided
12 by light source 20B. The filter 36A directs that light passed thereby to a portion of the image
13 recording medium 32 identified by reference numeral 32A. Similarly, the portion 35B of the light
14 from the beam splitting arrangement is filtered by a filter 36B that passes light in the wavelength
15 provided by light source 20B and blocks the light in the wavelength provided by light source 20A.
16 The filter 36B directs that light passed thereby to a portion of the image recording medium 32
17 identified by reference numeral 32B. The disjoint portions 32A and 32B of the image recording
18 medium can be processed independently by the image processing subsystem 13. The image
19 processing subsystem 13 can process the image that is recorded in portion 32B of the image
20 recording medium 32, that is, the portion that is associated with the structured illumination, to
21 provide mensuration information, virtual reconstruction, and so forth. On the other hand, the image
22 processing subsystem 13 can process the image that is recorded in portion 32A of the image
23 recording medium 32, that is, the portion that is associated with the uniform illumination, to provide
24 alignment information by which the local coordinate system that is associated with the positions of
25 the cameras at which the images were recorded can be related to the global coordinate system.

26 A further aspect of the invention, which also is in the lighting condition/target surface
27 technique class, will be described in connection with FIG. 1. Instead of using differences in
28 wavelengths of the light as reflected by the surfaces of the objects 16 and the targets 17 to

1 distinguish between the objects and targets, in this aspect polarization characteristics are used to
2 distinguish between the objects 16 and targets 17. The surfaces of the targets 17 are configured to
3 reflect light such as to preserve polarization, whereas the surfaces of objects 16 preferably reflect
4 light in such a manner that polarization is not preserved. This can be accomplished by providing that
5 the surfaces of targets 17 are retro-reflective, which reflect light in such a manner that the
6 polarization of illumination incident thereon will be preserved, and the surfaces of objects 16 are
7 diffuse, which reflect light in such a manner that the polarization of illumination incident thereon
8 will not be preserved. The illumination provided by the light sources 20A that are to provide
9 uniform illumination for the targets 17 in the scene 15 is polarized in a selected direction, for
10 example, horizontal, whereas the structured illumination provided by the light sources 20B that are
11 to provide illumination for the objects 16 is polarized in the orthogonal direction, for example,
12 vertical. Preferably, the intensity of the illumination provided by the light sources 20A is much
13 lower than the intensity of the illumination provided by the light sources 20B.

14 The surfaces of targets 17 will reflect illumination provided by both light sources 20A and
15 20B. Since the retro-reflective surfaces of the targets 17 preserve polarization, the reflected light
16 will have a horizontal component that corresponds to the uniform illumination provided by light
17 sources 20A, and a vertical component that corresponds to the structured illumination provided by
18 light sources 20B. The surfaces of objects 16 will also reflect illumination provided by both light
19 sources 20A and 20B, but it will be appreciated that, since the intensity of the uniform illumination
20 provided by light sources 20A will be much lower than the intensity of the structured illumination
21 provided by light sources 20B, the light reflected by the surfaces of objects 16 will be primarily the
22 structured illumination. However, since the surfaces of objects 16 are diffuse, the light reflected
23 thereby will not preserve polarization of the light incident thereon, in which case the reflected
24 structured light will have horizontal as well as a vertical components.

25 In addition, each camera 14n will be provided with a polarizer (not separately shown) ahead
26 of its optical path that allow only horizontally polarized light, or horizontal components of light that
27 is not horizontally polarized, to pass into the respective camera and be recorded thereby. As noted
28 above, the targets 17 will reflect the uniform illumination provided by the light sources 20A, which

1 is polarized horizontally, as well as that of the structured illumination provided by the light sources
2 20B, which is polarized vertically, in such a manner as to preserve polarization. However, in each
3 camera 14n, the respective polarizer will allow only the horizontally-polarized uniform illumination
4 from the targets 17 to pass and recorded on the respective image. Accordingly, the images of the
5 targets 17 in the respective images will be uniform. On the other hand, since the surfaces of the
6 objects 16 are diffuse, they do not preserve polarization. Accordingly, the structured illumination
7 as reflected by the objects 16 will have both a horizontal and a vertical component, and the
8 respective polarizer will allow the horizontal component of the structured illumination to pass, along
9 with the horizontal component of the uniform illumination as provided by the light sources 20A, for
10 recording on the respective image. Since, as noted above, the intensity of the uniform illumination
11 provided by light sources 20A is much lower than the intensity of the structured illumination
12 provided by light sources 20B, the light as reflected off the surfaces of objects 16 and recorded on
13 the respective image will primarily be structured.

14 After the cameras 14n have recorded the images, they will be processed by the image
15 processing subsystem 13, which will, inter alia, determine the locations of the targets 17 in the
16 respective images. For each image, the image processing subsystem 13 can use, for example, a
17 search methodology to search for regions of the image that are generally of uniform intensity, which
18 regions it can determine contain images of the respective targets 17 in the respective image. On the
19 other hand, the image processing subsystem 13 can determine that regions of the respective image
20 that are bright, but not generally uniformly bright, contain images of the objects 16 as illuminated
21 by the structured illumination.

22 A further aspect of the invention, which also is in the lighting condition/target surface
23 technique class, will be described in connection with FIG. 1. In this aspect, instead of distinguishing
24 between the objects 16 and the targets 17 in the images based on the wavelengths or polarization of
25 the light as recorded in the respective images, the objects 16 and targets 17 are distinguished based
26 on their positions. In that case, the cameras 14n are preferably high-resolution cameras having a
27 relatively large field of view ("FOV"). The center of view of the cameras 14n is directed primarily
28 toward the objects 16 in the scene 15. The targets 17 are preferably positioned some distance from

1 the objects 16, but still within the field of view of the cameras 14. The light sources 20A that are
2 to provide uniform illumination for the targets 17 are directed to the portions of the scene 15 in
3 which the targets 17 are located. On the other hand, the light sources 20B that are to provide the
4 structured illumination are directed to the portions of the scene 15 in which the objects 16 are
5 located. Thus, the uniform illumination is limited to the periphery of the field of view of the cameras
6 14n, where the targets 17 are located, whereas the structured illumination is limited to the portions
7 of the scene somewhat distant from the targets 17, in the portions of the scene 15 in which the
8 objects 16 are located. This will allow the image processing subsystem 13 to readily identify the
9 targets 17 in the scene 15 and determine their positions with a minimum of noise, while still
10 providing structured illumination that is useful in connection with the mensuration, virtual
11 reconstruction, and so forth, processing operations. As another alternative, the uniform illumination
12 sources 20A is be directed to all scene 15 that lies within the field of view of cameras 14n but their
13 intensity is much lower than the intensity of the structured illumination sources 20B, so objects 16
14 are primarily illuminated with structured light.

15 The light sources 20 used in connection with any of the aspects in the lighting
16 condition/target surface technique class may be any conventional types of light sources for providing
17 illumination of the required wavelengths, illumination of the required polarization direction(s), or
18 illumination having the required pattern of uniform illumination proximate the periphery of the
19 cameras' field(s) of view and structured illumination elsewhere, every feature in connection with the
20 relevant aspects mentioned above.

21 As an alternative, the system 10 can make use of a computer controlled pattern generator,
22 such as a computer-controlled LCD (liquid crystal display) pattern generator or DMD (digital micro-
23 mirror device), and so forth, that is configured to provide a uniform illumination for the portions of
24 the scene 15 that contain the targets 17 and a structured illumination for the portions of the scene
25 15 that contain the objects 16. In that alternative, the pattern generator initially provides a uniform
26 illumination over the entire scene 15, and the cameras 14n will record a set of images of the scene
27 15. The image processing subsystem 13 can distinguish between the targets and objects in a
28 conventional manner based on gray level, edge shape, or other methodologies as will be apparent

1 to those skilled in the art. The image processing subsystem 13 will then determine the locations of
2 the targets 17 in the scene 15 and enable the pattern generator to continue to provide the uniform
3 illumination in regions of the scene 15 in which the targets are located, and to provide a structured
4 illumination elsewhere within the fields of view of the cameras 14n, after which the cameras 14n will
5 be enabled to record a second set of images. The second set of images will include the targets 17,
6 which are illuminated by the uniform illumination, and the objects 16, which are illuminated by the
7 structured illumination, which can be processed by the image processing subsystem 13 as described
8 above. The intensities of the uniform illumination over the targets and the structured illumination
9 over the other portions of the field of views of cameras 14n can be with different levels as to utilize
10 efficiently the dynamic range of the system. It will be appreciated that the interval between the
11 points in time at which the first set of images and the second set of images are recorded by the
12 respective cameras 14n need not be small, since the first set of image is only needed to determine
13 the locations of the targets in the scene 15 for controlling the pattern generator for the second set of
14 images.

15 Another aspect of the invention will be described in connection with FIG. 1. If a camera 14n
16 is capable of recording successive images sufficiently rapidly, it may not need to be provided with
17 such light-ray splitting optical arrangements, nor need it record images in color, and the targets 17
18 and light sources need not have illumination of special wavelengths and or polarization directions.
19 If the cameras 14n can record successive images sufficiently rapidly, each camera 14n can record
20 successive images, with one image being recorded with light sources 20A, but not light sources 20B,
21 illuminating the scene 15, and another image being recorded with light sources 20B, but not light
22 sources 20A, illuminating the scene 15. If each camera 14n can record the successive images
23 sufficiently rapidly, and if the light sources 20A and 20B can switch off and on sufficiently rapidly,
24 any motion of the cameras 14n, the objects 16 and/or the targets 17 during the short time interval
25 between the times at which the images are recorded would be so slight as to be effectively zero. In
26 one embodiment, the cameras 14n make use of an Interline transfer CCD sensor, which can transfer
27 an image to the image processing subsystem very rapidly. This allows the respective camera 14n
28 to record successive images with a very short time interval therebetween, typically on the order of

1 several microseconds. Since the short time interval between successive images is so short, the
2 amplitude of any mechanical vibration of the rig 11 or movement of the objects 16 will be small
3 enough that they can be ignored.

4 As noted above, the invention provides two broad classes of arrangement, with the second
5 broad class comprising a set of arrangements that make use of algorithms to identify and distinguish
6 targets 17 from the objects 16 in the images. Arrangements in the algorithm set may be find utility
7 if, for example, no lighting condition/target surface characteristic technique can be used, but the
8 algorithm-based techniques can be used along with the lighting condition/target surface characteristic
9 techniques.

10 Common to all of the techniques in the algorithm class is that the cameras 14n in the digital
11 imaging system 10 initially record two sets of images, namely, a set of baseline images and a set of
12 working images. When recording the set of baseline images, the light sources 20 illuminate the
13 targets 17 with uniform illumination. The objects 16 are either not illuminated, or the system is
14 configured in such a way that the targets 17 are superior in their response. Since the objects 16 are
15 not illuminated for the baseline image set, or, if they are illuminated, they are illuminated and
16 recorded such that their sensitivity is negligible, images thereof will not be recorded in the baseline
17 image set. However, since the targets 17 are uniformly illuminated, the locations of their images can
18 be accurately determined in each of the baseline images in the baseline image set, and so their
19 locations relative to the local coordinate system can also be accurately determined. For the working
20 image set, the light sources 20 illuminate the scene 15, including both the targets 17 and the objects
21 16, using structured illumination, which, as noted above, can introduce noise in determining the
22 locations of the targets 17 in the respective working image. The image processing subsystem 13 will
23 use the working images in connection with mensuration, generation of a virtual reconstruction, and
24 the like, in the local coordinate system in a conventional manner. On the other hand, since the
25 images of the targets 17 in the working images will generally be deformed due to the structured
26 illumination, the image processing subsystem 13 will use the images of the targets 17 in the baseline
27 images to relate a local coordinate system to the global coordinate system in a conventional manner,
28 provided the local coordinate system of the working images and the local coordinate system of the

1 baseline images are the same. However, since the local coordinate system associated with the
2 baseline images may differ slightly from the local coordinate system for the targets as recorded in
3 the working images, the image processing subsystem 13 will make use of one or more of the
4 algorithmic techniques that will be described below, to locate the images of the targets as recorded
5 in the respective working images and generate a transformation that relates the local coordinate
6 system(s) associated with the baseline images and the local coordinate system(s) associated with the
7 working images. That transformation can, in turn, be used to determine the transformation between
8 the local coordinate system associated with the working images and the global coordinate system.

9 Preferably, the cameras 14n will record the baseline images and the associated working
10 images within a relatively short time interval, so that the transformation between the local coordinate
11 systems associated therewith is relatively small. In addition, if a baseline image and the associated
12 working image are recorded within a relatively short time interval, the targets 17 will be in
13 approximately the same locations in the two images. However, the targets 17 may not be in
14 precisely the same locations, since there may have been some movement, vibration, and the like by
15 the digital imaging system 10 and/or the objects 16 and targets 17 in the scene 15 during the time
16 interval. The transformation(s) as between the baseline images in the baseline image set and the
17 associated working images in the working image set accounts for such movement.

18 In determining the transformation as between each working image and the associated
19 baseline image, the image processing subsystem 13 makes use of one or more of a plurality of
20 algorithmic techniques to attempt to locate the exact positions of the images of the targets in the
21 baseline image and determine the relations between the positions of the targets 17 as between the
22 baseline image and the working image. In accordance with all of the techniques in the algorithmic
23 class, the image processing subsystem 13, after locating the images of the targets 17 in the baseline
24 image, determines masks of regions in the working image proximate the same relative location as
25 the images of the respective targets in the baseline image. In that operation, the image processing
26 subsystem 13 uses the baseline image of a baseline image/working image pair to generate a mask
27 defined by the images of the targets in the baseline image. Each element of the mask is centered on
28 a respective target and has a size that is a selected ratio to the size of the respective target. The mask

1 is used to define regions of the working image that will be processed using any of the techniques in
2 the algorithm class, thus the sizes of the mask elements will be such as to preferably include the
3 images of the targets 17 in the working image, but exclude images of the objects 16 in the working
4 image.

5 In accordance with one aspect of the algorithmic class, both images comprise pixels, and the
6 image processing subsystem 13, after locating the pixels comprising the images of the targets 17 in
7 the baseline image, can perform a pixel-by-pixel correlation between the working image and the
8 baseline image, thus determining their relative positions in the corresponding images. After image
9 processing subsystem 13 has identified the positions of the targets 17 in the baseline and working
10 images, it can determine the transformation therebetween in a conventional manner.

11 In accordance with another aspect of the techniques in the algorithmic class, the image
12 processing subsystem 13 performs a least squares fit in a region of the working image proximate the
13 same relative location as the image of the respective target in the baseline image. After determining
14 locations of the targets in the set of working images, the image processing subsystem 13 uses those
15 locations and the locations of the respective targets in the baseline images to determine the
16 transformation between the working and baseline images.

17 In accordance with yet another aspect of the techniques in the algorithmic class, the image
18 processing subsystem 13 detects edges of the images of the targets in the baseline image and
19 searches for a correlation between the edges of the images of the respective targets 17 in each
20 baseline image and edges or portions of edges of the images of the corresponding targets 17 in the
21 respective working image. The image processing subsystem 13 will, for the image of each target
22 17 in the baseline image, initially determine the contour of the edge in the baseline image. The
23 image processing subsystem 13 thereafter performs a pixel-by-pixel search in the working image for
24 the edge of the image in the working image. After determining locations of the targets in the set of
25 working images, the image processing subsystem 13 uses those locations and the locations of the
26 respective targets in the baseline images to determine the transformation between the working and
27 baseline images.

1 In accordance with yet another aspect of the techniques in the algorithmic class, the image
2 processing subsystem 13 makes use of a distance transformation technique. In that technique, the
3 image processing subsystem 13 initially locates the images of the targets 17 in the working image,
4 using any convenient methodology, including, for example, a search technique described above.
5 Thereafter, the image processing subsystem 13 processes the working image to determine the
6 minimum distance of each pixel in the working image from a pixel comprising the edge of the image
7 of a target 17, thereby creating a new image. The new image will be relatively dark in regions in
8 which features of the baseline image are relatively near to features in the working image. Since in
9 the baseline image the only features are images of the targets 17, and since images of the targets 17
10 in both the baseline image and the working image will generally be in approximately the same
11 positions in the two images, it is more likely that the new image will be relatively light in areas that
12 are proximate the locations of the images of the respective targets in the working and baseline
13 images, and not relatively light in areas of the new image that correspond to the locations of the
14 images of the objects 16 in the working image. The image processing subsystem 13 then generates
15 the transformation for relating the working image and the baseline image using the new "distance
16 map" image instead of the working image.

17 A further aspect of the techniques in the algorithmic class makes use of the fact that, in one
18 embodiment, the targets 17 are generally circular or elliptical when viewed from a direction
19 orthogonal to one surface. In addition, if a target is viewed, or an image of the target is recorded,
20 from a direction that is not orthogonal to the circular surface, the target will appear as an ellipse.
21 Accordingly, in this technique, the image processing subsystem 13 makes use of a shape fitting
22 technique to determine the contour(s) of the image(s) of the target(s) in the baseline image. In that
23 technique, the image processing subsystem 13 initially processes the baseline image to determine
24 a shape for each image of a target in the baseline image. Thereafter, the image processing subsystem
25 13 uses the edge of the image of the corresponding target in the working image and attempts to find
26 the location in the working image that provides the best fit for the previously-generated shape. In
27 finding the location that provides the best fit, the image processing subsystem 13 determines the
28 location for which the edge of the image of the target 17 best corresponds to the afore-mentioned

1 shape. The location in the working image that provides the best fit for the shape is deemed to be the
2 location of the image of the target in the working image. The image processing subsystem 13 can
3 determine the location of the image of each target 17 in each of the working image in the same
4 manner, and uses the locations as determined in both the baseline and working images to determine
5 the transformation therebetween. It will be appreciated that, if the surfaces of the targets have a
6 different shape, such as circular, rectangular, or elliptical, the image processing subsystem 13 can
7 perform a similar operation to determine the shape of the smallest, for example, quadrilateral in the
8 baseline image that will encompass the target, and thereafter perform corresponding operations in
9 connection with the working image.

10 Since the images of targets may be deformed in the working images by the structured
11 illumination that was provided when they were recorded, some portions of the images of the targets
12 or the edges of the images of the targets may be missing in the working images. After the image
13 processing subsystem 13 locates the edge of the image of the corresponding target 17 in the working
14 image, a further embodiment of the algorithmic classes can generate a weighting value that
15 represents the extent to which the contours of the edges in the two images correspond. Accordingly,
16 if the edge of the image or the image itself of the target 17 in the working image is not extensively
17 deformed by the structured illumination, the weighting value will be relatively high, whereas if the
18 edge of the image is extensively deformed, the weighting value will be relatively low. The image
19 processing subsystem 13 will then use the images of the targets in the working and baseline images,
20 weighted by the respective weighting values generated therefore, to determine the transformation
21 therebetween. This transformation, computed between the target images in the baseline and working
22 image sets, is an affine transformation and unique in that it accounts for the rigid motion of all
23 targets in the scene, and not a separate transformation for each target.

24 FIGS. 3 through 7 depict flowcharts of operations performed by the image processing
25 subsystem 13 in connection with the techniques described above. Since the operations are apparent
26 from the above description, the flowcharts will not be described further herein.

1 The invention provides a number of advantages. In particular, the invention provides a
2 number of arrangements that allow for recording of images of objects 16 and targets 17 in a scene
3 15, providing structured illumination for the objects 16, while reducing or eliminating noise in
4 connection with the positions of the targets in the images that can arise from the use of structured
5 illumination.

6 Although the image processing subsystem has been described as generating a transformation
7 between the working and baseline image sets, which can be used in transforming the local coordinate
8 system associated with the working image set to the global coordinate system, it will be appreciated
9 that the image processing subsystem can instead use the locations of the targets in the image(s)
10 comprising the working image set, as determined using the baseline image set, to determine a
11 transformation directly between the local coordinate system associated with the working image set
12 and the global coordinate system.

13 It will be appreciated that a system in accordance with the invention can be constructed in
14 whole or in part from special purpose hardware or a general purpose computer system, or any
15 combination thereof, any portion of which may be controlled by a suitable program. Any program
16 may in whole or in part comprise part of or be stored on the system in a conventional manner, or it
17 may in whole or in part be provided in to the system over a network or other mechanism for
18 transferring information in a conventional manner. In addition, it will be appreciated that the system
19 may be operated and/or otherwise controlled by means of information provided by an operator using
20 operator input elements (not shown) which may be connected directly to the system or which may
21 transfer the information to the system over a network or other mechanism for transferring
22 information in a conventional manner.

23 The foregoing description has been limited to a specific embodiment of this invention. It will
24 be apparent, however, that various variations and modifications may be made to the invention, with
25 the attainment of some or all of the advantages of the invention. It is the object of the appended
26 claims to cover these and such other variations and modifications as come within the true spirit and
27 scope of the invention.

1 What is claimed as new and desired to be secured by Letters Patent of the United States is:

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